

Concluding Remarks/Summary

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These remarks summarize some of the discussion at the Now 2004; in addition some topics not touched on at the meeting are reviewed briefly.

1. Introduction

Sometimes one hears the lament[1] that while theorists are lionized, rarely do experimenters get the credit that they deserve. To redress this balance a little, I would like to begin by recalling the life and times of Charles Drummond Ellis; whose work made the invention of the neutrino inevitable. His romantic story starts with his “conversion” from an army career as an artillery officer to research in physics while interned in prison in Berlin during the first world war. During the period 1921-27, he collaborated with James Chadwick and William Wooster in a series of measurements of β -ray spectra which established beyond doubt that the spectra were continuous[2] and ended the on-going controversy with Lise Meitner. In my book Ellis is one of the first heroes in the neutrino story[3].

Recalling NOW 2000[4], the progress in the last four years has been impressive, even spectacular. Then, both SNO and Kamland were still in the future, and now we have results from them. Similarly, K2K results have also been published. Oscillation dips have been observed in atmospheric neutrinos by Super-K and in reactor anti-neutrinos by Kamland. Several new facilities are close to completion.

2. Terra Cognita I

With the results of SNO and Kamland combined with all the previous results, one can summarize the current knowledge[5,6] of the neutrino mass differences and mixings:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{MNSP} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad (1)$$

where

$$U_{MNSP} = U \cong \begin{pmatrix} c_{12} & -s_{12} & U_{e3} \\ s_{12}/\sqrt{2} & c_{12}/\sqrt{2} & -1/\sqrt{2} \\ s_{12}/\sqrt{2} & c_{12}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} \quad (2)$$

In the above, the smallness of θ_{13} , and the closeness of θ_{23} to 45° have been incorporated; the actual fits correspond to $\theta_{12} \cong 33 \pm 2^\circ$, $\theta_{23} \cong 45 \pm 11^\circ$, $|U_{e3}| < 0.15$, $|\delta m_{32}^2| \simeq 2.5 \cdot 10^{-3} eV^2$ and $\delta m_{21}^2 = m_2^2 - m_1^2 = +8 \cdot 10^{-5} eV^2$.

We know $m_2 > m_1$ for the MSW effect to be operative in the sun, but the location of m_3 w.r.t. m_2 is unknown. Likewise we do not know the offset of the three masses from zero.

The above simple picture is muddled by the LSND “effect”, where in π^+ decay at rest, $\pi^+ \rightarrow \mu^+ \nu_\mu$, $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$, the wrong neutrino $\bar{\nu}_e$ was seen at a fractional rate of about (2-3) 10^{-3} . The simplest extension of three neutrinos to include one more sterile ν_s is now constrained strongly by the totality of neutrino data and disfavored. Two sterile (in addition to the three flavor) neutrinos provides a consistent fit to all data so far[7]. One may ask why two light sterile neutrinos, but then why not? Sterile neutrinos were avoided altogether by allowing CPT violation[8], wherein δm_{solar}^2 and δm_{KL}^2 would be different. However, there is no indication in data for such a difference. A baroque solution would be to violate CPT and have one light sterile neutrino (or have decoherence)[9]. A proposal was made[10], based on a rare decay mode of μ^+ : $\mu^+ \rightarrow e^+ \bar{\nu}_e \bar{\nu}_\alpha$, violating lepton number by 2, with a fractional rate

of $\sim 3.10^{-3}$, which would not involve neutrino oscillations. But this too is now ruled out by TWIST results[11] on the precision measurement of the Michel parameter in μ -decay, and by the limits from KARMEN[12]. We now must await results from MINI-BOONE on $\nu_\mu \rightarrow \nu_e$ oscillations to be announced a year from now (summer 2005?). Eventually MINI-BOONE[7] might also measure $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations. If the LSND result is confirmed, there can be a significant (and positive) impact on the expected size of any CPV effect in neutrino oscillations[13].

In 2000, non-oscillatory explanations were still possible for both solar and atmospheric neutrino data. For example, atmospheric neutrino data could be explained by neutrino decay, decoherence or by Flavor Changing Neutral Currents(FCNC). The solar neutrino data could be accounted for by FCNC, Resonant Spin-Flip Precession(RSFP) or Lorentz Invariance Violation(LV). We have learned that all of these possibilities are now excluded[14], except as sub-leading effects. We can now probe non-standard interactions(NSI) of neutrinos in solar neutrino data as well atmospheric neutrino data. When NSI are allowed as sub-leading effects, the oscillation fits get modified; resulting in significant deviations in the fitted parameters. For example, in solar fits, the so-called dark-side solutions (*i.e.* $m_1 > m_2$) can emerge[5].

2.1. Solar and Reactor Neutrinos

It seems that we have to wait for a few months for the full detailed paper on SNO results of the salt phase and a year or more for results of the run with ^3He counters[15]. It would be of great interest to look for (and find) the expected upturn in the energy spectrum at about 6 MeV and the expected level of the day-night asymmetry of about 2.5%. These would be powerful confirmations of LMA solution and the MSW effect at work.

As for reactor $\bar{\nu}_e$ s in Kamland, we heard about the improvements in statistics, energy calibration and in fiducial volume. We also learned about the new background from ^{210}Pb which amounts to about 10 events above 2.6 MeV, and causes a small shift in the δm^2 value[16]. The additional background events below 2.6 MeV make it diffi-

cult to extract a geo-neutrino signal at present. Kamland presented results on spectrum distortion and an L/E analysis which showed the characteristic oscillatory pattern. Kamland collaboration is now working on further purification with ^7Be solar ν_e detection in mind, with a possible 2007 date[16].

3. Terra Incognita I

The idea behind the geo-neutrino measurement is to determine the distribution of U and Th in the crust and the mantle, to confirm that 40% of the earth's heat comes from is radioactivity[17]. When Kamland lowers the background, it should be able to have the first results on geo-neutrinos. However, at Kamioka as well as at Gran Sasso (site of Borexino), the reactor background is quite high[18]:

Site	Geo- ν Rate	Reactor BG
Kamioka	5.4	1.5
GSL	5.9	0.65
SNO	6.8	1.3
Hawaii	3	0.027
Tibet	7.2	0.054

It is clear that a 1KT Kamland style detector near Hawaii would be most suitable for a clean accurate measurement of geo-neutrinos, at least for the flux from the mantle[17].

The possibility of a Geo-reactor at the center of the earth's core has been raised by Herndon[19]. This would be a breeder fission reactor operating at a power of about 3-10TW. As the earth cooled; U , Th in alloys and sulphides could have sunk to the centre and formed an OKLO-style reactor. This would also explain the low amount of oxygen and the high amount of ^3He and can provide a fluctuating energy source for geomagnetism. This alternative to the dynamo mechanism is not yet widely accepted, but is beginning to be taken seriously. In any case, observation of $\bar{\nu}_e$ s from the reactor (or non-observation) would be a crucial test[20]. The Kamland-in-Hawaii would be an ideal detector for this purpose as well.

In her review, Turck-Chieze[21] emphasized that there is no unified view of stars yet, and that three dimensional calculations of stellar evolution are still in future. As for the solar neutrino fluxes,

the CNO fluxes are now expected to be somewhat lower. There seems to be a need for some new ingredients beyond SM to describe the sun fully.

The desiderata for future solar neutrino experiments seem to be[22]: (a) to see the up-turn at low energy in SNO, (b) to see the day-night asymmetry (2-3% in SNO, 1-2% in SK), (c) extract the CNO flux, (d) proof of LMA, e.g. by confirming ${}^7\text{Be}$ flux (Kamland and Borexino), (e) precision CPT test by Kamland-solar comparison, (f) possible new ν -physics and (g) measurement of the ratio of neutrino luminosity to that in photons: L_γ/L_ν .

Several future solar neutrino programs were discussed[22]. Borexino and SNO (LS) will be able to measure the *pep* line as well CNO flux. The ${}^{11}\text{C}$ background studies which aim to reduce it are crucial for this[23]. LENS aims to measure $\text{pp } \nu_e$'s via charged current interaction in real time. XMASS with 10T of Xe is an ambitious project and over 5 years can measure $\text{pp } \nu_e$'s in neutrino-electron scattering and measure $\sin^2 \theta_{12}$ at 1% level. Future Megaton H_2O facilities[24] can measure ${}^3\text{He} - p$ as well as day-night asymmetry accurately. Intermediate base line (70 km) reactor experiments can also measure $\sin^2 \theta_{12}$ to 3%, and help remove degeneracies in the neutrino parameters[25].

4. Terra Cognita II

In atmospheric neutrinos, there was real progress in modeling fluxes[26]. New flux calculations including 3-dimensional codes represent the state of the art, and have reached a new level of sophistication. The main (and irreducible) uncertainty affecting the extraction of oscillation parameters is now the uncertainty in the knowledge of primary fluxes. Experimentally the two main things are the observation of unambiguous signature of oscillations in the dip in L/E and the laboratory (K2K) confirmation of the atmospheric deficit[27]. I was most pleased to see the confirmation of the oscillatory behaviour, something that we have been waiting for since 1988!

We heard about the Long Baseline and neutrino factory plans for the future. In Japan, there is a well-developed program[27] with T2K already

underway[28] and planning going ahead for phase II. For T2K initially the beam will come from 0.75 MW proton beam at 50 GeV from JPARC to SuperK, with 295 km baseline. The main goal will be to measure θ_{23} and δm_{32}^2 with a higher precision, and search for a non-zero U_{e3} . In phase II with 4 MW power and a new MegaT detector, the goal will be to search for CP violation, which would be observable for $\delta > 20^\circ$ and $\sin^2 2\theta_{13} > 0.01$.

In the U.S.[29] MINOS will start taking data in 2005, and reach 10% accuracy in δm_{23}^2 and be able to test CPT because of the ability to separate ν and $\bar{\nu}$ events (with the atmospheric ν 's). Post-MINOS plans involve NOVA which can probe θ_{13} at a level of 0.01 (in $\sin^2 2\theta_{13}$), measure $\sin^2 2\theta_{23}$ at a 1-2% level, measure the sign of δm_{23}^2 and probe CP violation with the proton driver. The off-axis detector for NOVA should be as large as possible. The precise nature of the detector at a baseline of about 800Km is under discussion.

In Europe, the LBL program[30] with CNGS is proceeding on schedule, with first beam expected in May 2006. Construction of OPERA, with a reasonable sensitivity for ν_τ events, is also underway. ICARUS will use a different technique for ν_τ events. Another proposal is to use the CERN-TARANTO(CNFT) baseline to utilize the second maximum and reach $\sin^2 2\theta_{13}$ to 0.002 level. There was some discussion of using beta-beams with CERN-Frejus(or GSL) baseline and even using LHC to make high energy beta-beams[31].

5. Terra Incognita II

Absolute neutrino masses are probed in (i) end point measurements in (e.g. tritium) beta decay[32], (ii) neutrinoless double beta decay[33] and (iii) large scale structure in cosmology[34]. The three are sensitive to different combinations:

$$\begin{aligned} \text{Tritium :} \quad m_\beta &= \left[\sum_i |U_{ei}|^2 m_i^2 \right]^{1/2} \\ \beta\beta 0\nu : \quad m_{\beta\beta} &= \sum_i U_{ei}^2 m_i \\ LSS : \quad \Sigma &= \sum_i m_i \end{aligned} \quad (3)$$

If we neglect, for simplicity, $|U_{e3}|^2$ then

$$\begin{aligned} m_\beta &\cong [m_1^2 + s_{12}^2 \delta m_{21}^2]^{1/2} \\ m_{\beta\beta} &\cong \begin{cases} m_1 + s_{12}^2 \sqrt{\delta m_{21}^2} \approx m_1 \\ \frac{1}{2}m_1 - s_{12}^2 \sqrt{\delta m_{21}^2} \approx \frac{1}{2}m_1 \end{cases} \\ \Sigma &\cong 3m_1 + \sqrt{\delta m_{21}^2} \pm \sqrt{\delta m_{32}^2} \end{aligned} \quad (4)$$

where the two cases for $m_{\beta\beta}$ correspond to constructive or destructive Majorana phases and the two signs in Σ corresponds to normal and inverted hierarchy[35]. If we consider the range of values implied by the results for $m_{\beta\beta}$ that have been reported[33] (but not yet confirmed), and take a value in the middle of this range,

$$m_{\beta\beta} \cong 0.5 \text{ eV} \quad (5)$$

then the value for Σ is 1.5 eV for constructive phase and 3 eV for destructive phase. But a value for Σ as high as 3eV is disfavored by the recent cosmological data[34]. Hence a constructive phase is favored, quasi-degeneracy is also favored and a value for $m_1 \sim m_\beta \sim 0(\text{eV})$ is expected. The next round of tritium experiments (e.g. KATRIN)[32] should be able to confirm this. This is true for any value of $m_{\beta\beta}$ larger than about 0.25 eV. The current constraints may tighten and make life very interesting. We await results from future double beta decay experiments[37], KATRIN and further refinement and improvement of cosmological bounds. The extraction of the effective mass from neutrinoless double beta decay rates depends crucially on the improvements in the knowledge of the nuclear matrix elements[38]. Needless to say, neutrinoless double beta decay is very important to establish the Majorana natures of the neutrino; unfortunately a null result does not establish a Dirac nature. It is quite remarkable that explanations of baryon asymmetry based on leptogenesis place bounds on neutrino masses in the (0.15 to 1) eV range[39].

6. Terra Incognita III(?)

There was a lively discussion of theory issues during the meeting[35,40]. In my view, while there have been many interesting proposals, we

are still waiting for a breakthrough. This is true for not only neutrino mass matrix, but flavors in general. We would like to understand the smallness of neutrino masses, the near maximality of some mixing, the pattern of the masses, the near degeneracy if true. The presence of broken family symmetries is still an open question. Do GUTS play a role (any) in the mass and mixing patterns? Ferruglio[35] gave an elegant summary of the current status of theory.

What about making predictions? Recently there have been many attempts at predicting the remaining mixing element: U_{e3} . The prediction run the gamut from the maximum allowed value all the way to nearly zero[35]. There is an interesting proposal that I learned from Bjorken and from Javier Ferrandis[41]. The idea is the following. Suppose that the neutrino mass matrix is diagonalized by a matrix U_ν which has the form:

$$U_\nu \cong \begin{pmatrix} \cdot & \cdot & 0 \\ \cdot & \cdot & 1/\sqrt{2} \\ \cdot & \cdot & 1/\sqrt{2} \end{pmatrix} \quad (6)$$

The charged lepton mass matrix has the form analogous to the down quark mass matrix (which leads to a successful prediction for θ_c of $\theta_c \approx \sqrt{m_d/m_s}$):

$$M_\ell \sim \begin{pmatrix} 0 & a & \cdot \\ a & b & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix} \quad (7)$$

In this case $\theta_{12}^\ell \sim \sqrt{\frac{me}{2m_\mu}}$, and the full

$$U_{MNSP} = U_\ell^+ U_\nu \quad (8)$$

has now a $U_{e3} \sim \sqrt{\frac{me}{2m_\mu}} \sim 0.052$. This is the resulting prediction for U_{e3} and it is testable in future ambitious reactor proposals we heard about here[44].

Recently there has been some discussion of the so-called QLC relation[42]:

$$\theta_{CKM}^{12} + \theta_{MNSP}^{12} = \theta_c + \theta_{solar} \approx 45^0 \quad (9)$$

where $\theta_c \sim 13^0$ and $\theta_{solar} = 33 \pm 2^0$. In fact there is also the approximate relation:

$$\theta_{CKM}^{23} + \theta_{MNSP}^{23} \simeq 45^0 \quad (10)$$

within errors[43]. We have no idea if these are accidents or genuine hints with some deeper meaning. A generalised QLC relation is then suggested: $U_{CKM} \times U_{MNS} = U_{BM}$. This leads me to a third relation:

$$\theta_{CKM}^{13} + \theta_{MNSP}^{13} \simeq 0 \quad (11)$$

If the RHS above is really close to zero, the implication would be that

$$|U_{e3}| = |V_{ub}| \approx 0.004, \quad (12)$$

in which case $|U_{e3}|$ is out of reach of experiments[44]. I hope this is not the case.

7. Atlas Coelestis: Neutrinos from Heavens

I would like to discuss in the rest of the talk two topics which were not discussed at great length during the meeting. One is the uses of high energy astrophysical neutrinos and the other is detection of relic neutrino background. While the production[45] of and detection[46] of high energy astrophysical neutrinos was discussed, all the various uses they can be put to was not discussed in any detail. Likewise, while relic neutrinos were discussed their possible detection was not discussed. I review these topics very briefly.

We make two basic, reasonable assumptions: one is that distant high energy neutrino sources exist; and two that in the near future, very large volume, well instrumented detectors of sizes of order of KM3 (as discussed here)[46] and beyond will be operating.

From these sources, we expect half as many ν'_e s as ν'_μ s and virtually no ν'_τ s. This comes about simply because the neutrinos are thought to originate in decays of pions (and kaons) and subsequent decays of muons. The flux ratio of $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ is canonical for most sources[45].

With the current knowledge of neutrino masses and mixings as summarized earlier and with $\delta m^2 L/4E$ so large that the oscillations are always averaging out, a flux ratio of $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ gets converted into one of 1: 1: 1. Hence the flavor mix expected at arrival is simply an equal

mixture of ν_e, ν_μ and ν_τ as was observed long ago[47,48].

If this universal flavor mix is confirmed by future observations, our current knowledge of neutrino masses and mixings is reinforced and conventional wisdom about the beam dump nature of the production process is confirmed as well. However, it would much more exciting to find deviations from it, and learn something new. How can this come about? There are quite a few ways in which this can happen. Below is a shopping list of a variety of ways in which this could come to pass.

The first and simplest is that initial flavor mix is NOT 1 : 2 : 0. This can happen when there are strong magnetic fields causing muons to lose energy before they decay, and there exist models for neutrino production in AGN's in which this does happen[49]. In this case the ν'_e s have much lower energies compared to ν'_μ s and effectively the initial flavor mix is 0 : 1 : 0 and averaged out oscillations convert this into 1/2 : 1: 1 on arrival.

The possibility that the mass differences between neutrino mass eigenstates are zero in vacuum (and become non-zero only in the presence of matter) has been raised recently[50]. If this is true, then the final flavor mix should be the same as initial namely: 1 : 2 : 0.

Neutrino decay is another important possible way for the flavor mix to deviate significantly from the democratic mix[51]. If neutrinos decay, then in general, the heavier neutrinos are expected to decay into the lighter ones via flavor changing processes. It has been shown that the only possible interesting modes are two body modes into a lighter neutrino and massless boson[52]. With neutrinos from these sources we can probe lifetimes many orders of magnitude longer than the current bounds. Relic supernova signals of $\bar{\nu}'_e$ s can probe even longer lifetimes[53].

For normal hierarchy in which both ν_3 and ν_2 decay, only the lightest stable eigenstate ν_1 survives. In this case the flavor ratio is $U_{e1}^2 : U_{\mu 1}^2 : U_{\tau 1}^2$ [54]. Thus if $U_{e3} = 0$, then

$$\phi_{\nu e} : \phi_{\nu \mu} : \phi_{\nu \tau} \simeq 5 : 1 : 1, \quad (13)$$

for the neutrino mixing parameters given above. This is an extreme deviation of the flavor ratio

from that in the absence of decays and should be easy to distinguish. For inverted hierarchy, ν_3 is the lightest and hence stable state, and so[51]

$$\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = U_{e3}^2 : U_{\mu 3}^2 : U_{\tau 3}^2 = 0 : 1 : 1. \quad (14)$$

When U_{e3} is not zero, and the hierarchy is normal, it is possible to obtain information on the values of U_{e3} as well as the CPV phase δ [55]. The flavor ratio e/μ varies from 5 to 15 (as U_{e3} goes from 0 to 0.2) for $\cos\delta = +1$ but from 5 to 2 for $\cos\delta = -1$. The ratio τ/μ varies from 1 to 5 ($\cos\delta = +1$) or 1 to 0.2 ($\cos\delta = -1$) for the same range of U_{e3} .

If the decays are not complete and if the daughter does not carry the full energy of the parent neutrino; the resulting flavor mix is somewhat different but in any case it is still quite distinct from the simple 1 : 1 : 1 mix[51].

If neutrinos have flavor (and equivalence principle) violating couplings to gravity (FVG), or Lorentz invariance violating couplings; then there can be resonance effects which make for one way transitions (analogues of MSW transitions) e.g. $\nu_\mu \rightarrow \nu_\tau$ but not vice versa. In case of FVG for example, this can give rise to an anisotropic deviation of the ν_μ/ν_τ ratio from 1, becoming less than 1 for events coming from the direction towards the Great Attractor, while remaining 1 in other directions[56].

Another possibility that can give rise to deviations of the flavor mix from the canonical 1 : 1 : 1 is the idea of neutrinos of varying mass (MaVaNs), in which neutrino masses are related to the dark energy[57]. The end result is that the neutrino mass depends inversely on neutrino density, and hence on the epoch. As a result, if the sterile neutrino mixes with a flavor neutrino, the mass difference varies along the path, with potential resonance enhancement of the transition probability into the sterile neutrino, and thus change the flavor mix. For example, if one resonance is crossed enroute, it can lead to a conversion of the lightest (mostly) flavor state into the (mostly) sterile state, thus changing the flavor mix to $1 - U_{e1}^2 : 1 - U_{\mu 1}^2 : 1 - U_{\tau 1}^2 \approx 1/3 : 1 : 1$, in case of inverted hierarchy and similarly $\approx 2 : 1 : 1$ in case of normal hierarchy[58].

If each of the three neutrino mass eigenstates is

actually a doublet with very small mass difference (smaller than $10^{-6}eV$), then there are no current experiments that could have detected this. It turns out that the only way to detect such small mass differences ($10^{-12}eV^2 > \delta m^2 > 10^{-18}eV^2$) is by measuring flavor mixes of the high energy neutrinos from cosmic sources[59].

The flavors deviate from the democratic value of $\frac{1}{3}$ by

$$\begin{aligned} \delta P_e &= -\frac{1}{3} \left[\frac{3}{4}\chi_1 + \frac{3}{4}\chi_2 \right], \\ \delta P_\mu = \delta P_\tau &= -\frac{1}{3} \left[\frac{1}{8}\chi_1 + \frac{3}{8}\chi_2 + \frac{1}{2}\chi_3 \right] \end{aligned} \quad (15)$$

where $\chi_1 = \sin^2(\delta m_i^2 L/4E)$. The flavor ratios deviate from 1 : 1 : 1 when one or two of the pseudo-Dirac oscillation modes is accessible. In the ultimate limit where L/E is so large that all three oscillating factors have averaged to $\frac{1}{2}$, the flavor ratios return to 1 : 1 : 1, with only a net suppression of the measurable flux, by a factor of $1/2$.

To summarize, the measurement of neutrino flavor mix at neutrino telescopes is absolutely essential to uncover new and interesting physics of neutrinos[60]. In any case, it should be evident that the construction of very large neutrino detectors is a “no lose” proposition.

8. Atlas Coelestis: Relic Neutrino Detection

Turning to the relic neutrinos, we know[61] that the effective temperature “ T_ν ”, today is about $1.9^0K \sim 1.7 \times 10^{-4} eV$. The number density ($\nu + \bar{\nu}$) is about 115/cc. (This assumes that we do not live in a “neutrino-free” universe![62]). How can we detect these neutrinos?

The average momentum of relic neutrinos is $3.2T_\nu \sim 5.2 \times 10^{-4} eV/c$. The neutrino current density is $cn_\nu \sim 10^{13} cm^{-2} s^{-1}$ for massless neutrinos and $5.10^9 cm^{-2} s^{-1}$ for mass of O(eV). The effective interaction Hamiltonian for neutrinos with neutral matter is proportional to $a_e = (3Z - A)$ for ν_e and $a_\mu = (A - Z)$ for ν_μ and ν_τ . The ν_α -scattering cross section (at very low energies) on

nuclei then goes as

$$\sigma_\alpha \sim \frac{a_\alpha^2 G_F^2 m_\nu^2}{\pi} \quad (16)$$

Many early proposals to detect relic neutrinos by reflection or coherent effects turned out to be incorrect. There are three methods which some day may prove to be practical.

The first is a proposal due to Stodolsky. The idea needs neutrino degeneracy i.e. excess of ν (or $\bar{\nu}$) over $\bar{\nu}$ (or ν) to work. Then a polarized electron moving in a background of CMB neutrinos can change its polarization due to the axial vector parity violating interaction. The effective neutrino density (for $n_\nu \gg n_{\bar{\nu}}$) goes as $p_f^2/6\pi^2$ where p_f is the Fermi momentum. The effective interaction goes as

$$H_{eff} \sim \frac{2G_F}{\sqrt{2}} \bar{\sigma}_e \cdot \bar{\nu} n_\nu \quad (17)$$

With $v \sim 300 \text{ km/sec}$ and $p_f \sim O(\text{eV})$ this leads to a rotation of the polarization of about 0.02° in a year. Can such small spin rotations can be detected? Certainly not at present, but technology may someday allow this.

For a magnetized macroscopic object, this interaction can also give rise to a torque and lead to an acceleration which can be estimated as

$$a \sim 10^{-27} \text{ cm/sec}^2 \quad (18)$$

for some typical dimensions[64]. Several proposals have been made but all seem to need future technological breakthrough[65].

The second method is one suggested by Zel'dovich and collaborators[66]. The idea is to take advantage of momentum transfer in neutrino-nucleus scattering. Consider an object made up of small spheres of radius $a \approx \lambda$ (neutrino wavelength) packed loosely with pore sizes also of the same size (to avoid destructive interference). If the number of atoms in the target is N_A then the effective coherent cross-section is

$$\sigma = \sigma_\alpha N_A^2 \quad (19)$$

where σ_α is as given in Eq. 16. Assuming total reflection, momentum transfer is

$$\Delta p \cong 2m_\nu v_\nu \quad (20)$$

and the force $f = j_\nu \sigma \Delta p$ is given by

$$f = 2n_\nu \sigma_\alpha N_A^2 m_\nu v_\nu^2 \quad (21)$$

The most optimistic estimates are obtained by assuming some clustering ($n_\nu \sim 10^7/\text{c.c.}$), $m_\nu \sim 0(\text{eV})$, $v_\nu \sim 10^7 \text{ cm/s}$, $\rho \sim 10 \text{ gm/cc}$; leading to

$$a = \frac{f}{m} = \frac{f}{N_A m_N} \sim 10^{-23} (a_\alpha/A)^2 \text{ cm.s}^{-2} \quad (22)$$

Such accelerations are at least ten orders of magnitude removed from current sensibility and possible detection remains far in future[67]. In addition, this effect is absent for Majorana neutrinos or suppressed very much[64].

The third possibility is based on the proposal by Weiler in 1982[68]. The basic idea is as follows. If neutrinos have masses in the eV range and there are sources of very high energy neutrinos at large distances, then they can annihilate on the relic $\bar{\nu}$ and make a Z^0 on-shell at resonance creating an absorption dip in the neutrino spectrum. The threshold for Z production would be at $E \sim m_Z^2/2m_\nu$ which is about 4.10^{21} eV for $m_\nu \sim 0(\text{eV})$. This seemed like an unlikely possibility, since it required large neutrino fluxes at very high energies to see the neutrino spectrum and then the absorption dip. But all this changed dramatically recently with the hints of a signal of cosmic rays beyond the GZK cut-off. The GZK cut-off is the energy at which cosmic ray protons pass the threshold for pion production off the CMB photons. This is at an energy $E \sim m_\pi m_p/E_\gamma \sim 6.10^{19}$ eV. Above this energy, the mean free path of protons is less than 100Mpc and hence these protons have to originate "locally". The flux for higher energies should then decrease dramatically since we believe the cosmic rays are not produced locally. Recently, what used to be hints of the cosmic ray signal extending beyond this cut-off, may have become a clear signal. The events are most likely due to protons. Then an explanation is called for. One intriguing proposal is that these events are nothing but a signal for the Z 's produced by the $\nu\bar{\nu} \rightarrow Z$ process with the protons coming from the subsequent Z decay[71]! Of course, the original problem of needing sources of high energy neutrinos remains. If this explanation is valid, we may have

already seen (indirect) evidence for the existence of relic neutrinos. In principle, this proposal can be tested: (i) the events should point back out at the neutrino sources; (ii) there is an eventual cut-off when the energy reaches the threshold energy for Z production, $E \sim 4.10^{21} \left(\frac{eV}{m_\nu} \right)$ eV; (iii) γ/p ratio should be large near threshold and (iv) the large ν -flux should be eventually seen directly in large ν -telescopes. This pretty picture may be on the verge of being ruled out by the ever tightening bounds on flux of diffuse high energy neutrinos[72]. I am afraid it may be a very long time before we have clear cut, unambiguous direct detection of relic neutrinos.

9. Acknowledgements

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